Star clusters: Basic galactic building blocks throughout time and space
Proceedings IAU Symposium No. 266, 2009
R. de Grijs and J. Lépine, eds.

DOI: 00.0000/X000000000000000X

Young massive star clusters: Achievements and challenges

Richard de Grijs

Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China
email: grijs@kiaa.pku.edu.cn

Department of Physics & Astronomy, The University of Sheffield, Sheffield S3 7RH, UK
email: R.deGrijs@sheffield.ac.uk

National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

Abstract. In spite of significant recent and ongoing research efforts, most of the early evolution and long-term fate of young massive star clusters remain clouded in uncertainties. Here, I discuss our understanding of the initial conditions of star cluster formation and the importance of initial substructure for the subsequent dynamical-evolution and mass-segregation timescales. I also assess our current understanding of the (initial) binary fraction in star clusters and the shape of the stellar initial mass function at the low-mass end in the low-metallicity environment of the Large Magellanic Cloud. Finally, I question the validity of our assumptions leading to dynamical cluster mass estimates. I conclude that it seems imperative that observers, modellers and theorists combine efforts and exchange ideas and data freely for the field to make a major leap forward.

Keywords. stellar dynamics, methods: N-body simulations, binaries: general, stars: luminosity function, mass function, open clusters and associations: general, galaxies: star clusters, Magellanic Clouds

1. Introduction

It is now widely accepted that stars do not form in isolation, at least for stellar masses above $\sim$0.5 $M_\odot$. In fact, 70–90% of stars may form in a clustered mode (cf. Lada & Lada 2003). Star formation results from the fragmentation of molecular clouds, which in turn preferentially leads to star cluster formation. Over time, clusters dissolve or are destroyed by interactions with molecular clouds or tidal stripping by the gravitational field of their host galaxy.

A significant amount of recent research has focused on whether at least some of the young massive star clusters (YMCs) associated with the most violent starburst events in the local Universe may evolve into counterparts of the ubiquitous globular clusters (GCs) observed in almost all local galaxies. The main motivation for these studies was essentially twofold. First, for any compact, bound cluster to survive for a cosmologically significant length of time, its stellar initial mass function (IMF) must have a sufficient number of low-mass stars (acting as dynamical 'glue') to keep it together for so long. This places strong constraints on the IMF shape of any surviving YMCs and GCs. Second, as presumed hallmarks of the most violent galaxy-wide starburst episodes, YMCs trace the star-formation (and, to some extent, the assembly) histories of their host galaxies. As such, they serve as the proverbial light houses in the dark.

Rather than regurgitating the well-known issues affecting our detailed understanding of YMC-to-GC evolution (for reviews see, e.g., de Grijs & Parmentier 2007; de Grijs 2010), in this contribution I will focus on recent results as regards the shape of the low-mass IMF in cluster environments (Section 2), the effects of the initial conditions on

cluster dynamics (Section 3) and the binary contributions in star clusters as a function of age (Section 4). In Section 5, I will conclude this contribution by highlighting some of the remaining uncertainties hampering a more detailed understanding of the underlying physics driving star cluster evolution and its observational interpretation.

2. The low-mass initial mass function

The shape of the stellar IMF in the solar neighbourhood for stellar masses > 1 M$_\odot$ has essentially remained unchallenged since Salpeter's (1955) seminal study. Neverheless, the origin of its apparent universality is still hotly debated (e.g., Bonnell et al. 2007; Goodwin & Kouwenhoven 2009). Better constraining the physical origin of the IMF will have a major impact on, e.g., our understanding of the conditions prevailing in a wide range of starburst events, and the formation of the first stars and clusters in the early Universe. However, for the latter we would need to follow the full radiative cooling processes from primordial gas and the subsequently formed metallic elements in full detail!

At low masses, most current models agree that the solar-neighbourhood IMF flattens. This can be modelled by either multiple power-law or lognormal mass distributions (cf. Kroupa 2001; Chabrier 2003). While the former provides a mathematically convenient and observationally useful scaling law, the latter is supported by realistic numerical simulations in an attempt to understand the underlying physics (Hennebelle & Chabrier 2008). These simulations take into account dynamical depletion of the lowest-mass stars and replace the idea of a single Jeans mass for all newly formed stars in a given molecular cloud by a distribution of local Jeans masses which are representative of the lognormal density distribution of the turbulent, fragmenting gas. As statistically significant samples of roughly coeval stars, rich young star clusters play a major role in constraining the low-mass IMF. Open questions remaining in this field relate to, among others, the initial structure of newly formed clusters and whether the ubiquitous mass segregation observed in clusters of any age is dynamical or perhaps primordial (i.e., related to the process of star formation).

Note, however, that Goodwin & Kouwenhoven (2009) recently argued that a universal IMF does not necessarily provide unambiguous information about the star-formation activity from which the individual stars originated. One needs to take into account the initial binary fraction and mass-ratio distribution as well as the core-mass function and star-formation efficiency. They showed convincingly that very different (binary) mass-ratio distributions can produce very similar IMFs from very similar *core*-mass functions, while the resulting IMFs are also (to first order) insensitive to the binary fraction.

Ignoring the Goodwin & Kouwenhoven (2009) suggestions for the moment, preliminary clues as to the shape of the low-mass IMF (down to $\sim$0.15–0.30 M$_\odot$) in the low-metallicity ($Z \sim 0.4$ Z$_\odot$) environment of young ($\sim$4–45 Myr) Large Magellanic Cloud (LMC) clusters have recently been uncovered on the basis deep *Hubble Space Telescope* imaging observations (e.g., Da Rio et al. 2009; Liu et al. 2009a,b). Da Rio et al. (2009) reach a lower-mass limit of $\simeq 0.43$ M$_\odot$ in constructing their IMF of the LH 95 stellar association, while Liu et al. (2009a,b) push their method as low as 0.15–0.30 M$_\odot$ in the populous, young ($\sim$20–45 Myr-old) clusters NGC 1805 and NGC 1818. These analyses are particularly challenging in view of the stellar population's evolutionary state, requiring pre-main-sequence modelling to derive robust stellar mass estimates, which is notoriously difficult.

While these results must therefore be taken with a degree of caution, they appear to imply that the IMFs of these young clusters are essentially the same as that in the solar neighbourhood, although the characteristic stellar masses are somewhat higher. Figure 1

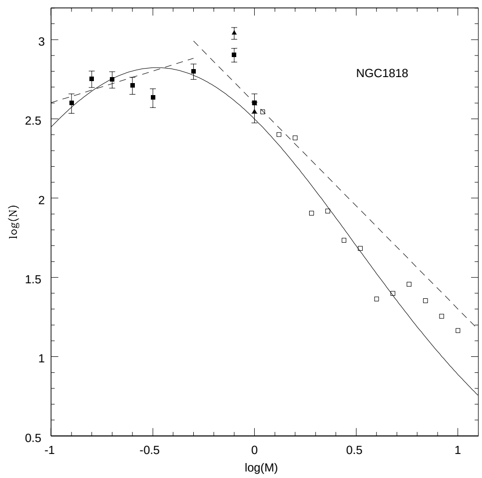

Figure 1. Complete mass function of NGC 1818. The dashed lines show the standard Kroupa (2001) IMF while the solid line represents the best-fitting lognormal distribution. See Liu et al. (2009a) for more details.

shows the complete mass function of NGC 1818 (Liu et al. 2009a) down to the 50% completeness limit. One would ideally want to probe younger star-forming regions to reach firmer conclusions, but these are inevitably obscured by large amounts of dust, hence requiring deep and often wide-field infrared (IR), (sub)millimetre, radio and X-ray surveys (as well as pointed observations) that are now coming online (e.g., the Spitzer Space Telescope's GLIMPSE survey or the UKIRT IR deep-sky survey, UKIDSS; e.g., Benjamin et al. 2003; Lucas et al. 2008) and which probe the low-mass stellar mass distribution in particular (see, e.g., Rathborne et al. 2009).

3. Early dynamical evolution

Simulations of star cluster evolution almost always assume that the stars are initially smoothly distributed and in dynamical equilibrium. However, both observations and the theory of star formation tell us that this is not how clusters form. We recently investigated the effects of substructure and initial clumpiness on the early evolution of clusters (Allison et al. 2009; see also references therein). Comparisons with observations will allow us to constrain how much initial substructure can be present. The most massive stars in young star clusters are almost always observed to be mass segregated (e.g., Hillenbrand & Hartmann 1998; de Grijs et al. 2002a,b,c; Gouliermis et al. 2004). A crucial question triggered by this observation relates to the physical origin of this characteristic mass distribution. Do massive stars form in the centres of clusters, or do they migrate there over time due to gravitational interactions with other cluster members? In smooth, relaxed clusters it has been argued that the most massive stars must form in the cores (e.g., Bonnell & Davies 1998; and references therein), which is therefore often referred to as primordial mass segregation (but see Ascenso et al. 2009). But does substructure perhaps play an important role?

Both observational evidence (e.g., Larson 1995; Testi et al. 2000; Elmegreen 2000; Lada & Lada 2003; Gutermuth et al. 2005; Allen et al. 2007) and theorical considerations suggest that young star clusters tend to form with a significant amount of substructure. Their progenitor molecular clouds are observed to have significant levels of substructure

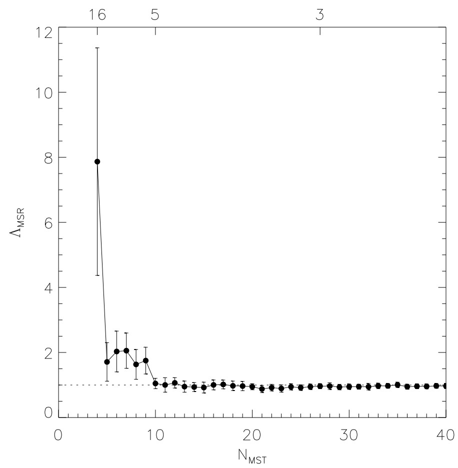

Figure 2. Mass-segregation ratio, $\Lambda_{\rm MST}$, for the Orion Nebula Cluster. The dashed line indicates the absence of mass segregation. See Allison et al. (2009) for more details.

in both density and kinematics (e.g., Carpenter & Hodapp 2008), which is likely induced by the supersonic turbulence thought to dominate molecular cloud structure (e.g., Mac Low & Klessen 2004; Ballesteros-Paredes et al. 2007). Observations also support a scenario in which young clusters lose their substructure on timescales of < 2 Myr (e.g., Cartwright & Whitworth 2004; Schmeja et al. 2008). Simulations suggest that the only way in which this could happen is if clusters are born dynamically cool (Goodwin et al. 2004; Allison et al. 2009). On the basis of these arguments, Allison et al. (2009) recently performed an ensemble of N-body simulations aimed at exploring the earliest phases of cluster evolution. They find that cool, substructured clusters appear to mass segregate dynamically for stellar masses down to a few $M_\odot$ on timescales of a few Myr. This is reminiscent of the observational status of the Orion Nebula Cluster (e.g., Bonnell & Davies 1998; Allison et al. 2009; Moeckel & Bonnell 2009).

Allison et al. (2009) modelled an initially highly substructured cluster (using multiple realisations to assess the numerical uncertainties), characterised by a ratio of the kinetic to potential energy of 0.3 (where 0.5 is virialised) and a fractal dimension of 1.6 (where 3 corresponds to a spherically symmetric distribution), containing 1000 stars drawn from a Kroupa (2001) IMF spanning the mass range from 0.08 to 50 $M_\odot$. Given the cluster's nonsphericity, we used a novel approach to determine the degree of mass segregation, quantified by using the concept of the 'minimum spanning tree' (MST). A sample's MST corresponds to the path connecting all points in the sample with the shortest possible path length, and which contains no closed loops (see, e.g., Prim 1957). We defined a 'mass-segregation ratio',

$$\Lambda_{\rm MSR} = \frac{\langle l_{\rm norm}\rangle}{l_{\rm massive}} \pm \frac{\sigma_{\rm norm}}{l_{\rm massive}}, \tag{3.1}$$

where $\langle l_{\rm norm}\rangle$ is the average length of the MST of sets of $N_{\rm MST}$ random stars and $l_{\rm massive}$ is the length of the MST of the $N_{\rm MST}$ most massive stars. The dispersion associated with the average length of the random MSTs is roughly Gaussian and can therefore be quantified by the standard deviation, $\sigma_{\rm norm}$. Using this definition, if $\Lambda_{\rm MST} > 1$, a given sample of cluster stars is mass segregated.

Figure 2 shows an application of this method to the 900 stars in the Orion Nebula

Cluster for which masses are available (Hillenbrand 1997). The method clearly identifies the mass segregation of the central Trapezium system at $N_{\rm MST} = 4$, $\Lambda_{\rm MST} = 8.0 \pm 3.5$, but it also shows that there appears to be a secondary level of mass segregation involving the nine most massive stars > 5 M$_\odot$ (cf. Hillenbrand & Hartmann 1998; see Allison et al. 2009 for additional details).

More work is required to systematically address the most likely initial conditions for cluster formation leading to the observed configurations. In particular, we have thus far not included binary stars, although they are expected to have an effect on the MST lengths. If a binary is resolved, it is very likely that the two components will be linked as a node, as will higher-order systems. Allison et al. (2009) suggest that this raises the possibility that MSTs could be very useful in locating binary and multiple systems by looking for short links within the MST (but see Cartwright & Whitworth 2005). In addition, many cluster observations suffer from significant incompleteness, particularly near the most massive stars where low-mass stars cannot be detected even if they are present. This poses a significant problem as it is impossible to know if there are many low-mass stars in the 'central' regions (in whatever way defined in the presence of substructure).

4. The contribution of binaries to star cluster evolution

More often than not, simulations of star clusters neglect the presence of binary stars. Observations of local star-forming regions lead us to suspect that all, or nearly all, stars form in binary or triple systems (Goodwin & Kroupa 2005; Duchêne et al. 2007; Goodwin et al. 2007). Such systems significantly affect the dynamical evolution of the cluster, yet the initial binary fractions in dense star clusters are poorly known. Almost all studies of binarity have been limited to nearby solar-metallicity populations (see Duchêne 1999 and Duchêne et al. 2007 for reviews). However, it might be expected that metallicity (e.g., through its effects on cooling and hence on the opacity limit for fragmentation) will play a role in the fragmentation of cores to produce binary systems (Bate 2005; Goodwin et al. 2007).

The binary fractions in more distant, massive clusters have not yet been studied thoroughly, because of observational limitations. Note, however, that statistical colour-magnitude analysis based on artificial-star tests offers a promising alternative (e.g., Romani & Weinberg 1991; Rubenstein & Bailyn 1997; Bellazzini et al. 2002; Cool & Bolton 2002; Zhao & Bailyn 2005; Davis et al. 2008). In addition, all clusters thus far studied in this way are old stellar systems, in which dynamical evolution is expected to have altered the initial binary population significantly. Efforts have begun to address this issue for the much more distant young populous clusters in the LMC (e.g., Elson et al. 1998). Hu et al. (2009) estimate that the binary fraction in NGC 1818 in the mass range between 1.3 and 1.6 M$_\odot$ is $\sim$0.35 for systems with an approximately flat mass-ratio distribution, q, for $q > 0.4$. This is consistent with a *total* binary fraction of F stars of 0.6 to unity. Note, however, that in view of recent developments and the discovery of multiple main sequences in a variety of star clusters (see, e.g., Piotto, this volume), this may need to be revised downwards.

In Fig. 3 (Hu et al. 2009), I show the cumulative distribution function (CDF) with pseudo-colour (defined as the colour change along the main sequence in the colour-magnitude diagram) as observed for the entire magnitude range of interest in NGC 1818 (solid line) and for a stellar population with photometric errors but no binaries (dotted line). This is clearly a very bad fit to the data. The figure also shows the best-fitting (r.m.s.) binary fraction ($f_{\rm b}$), assuming a uniform mass-ratio distribution,

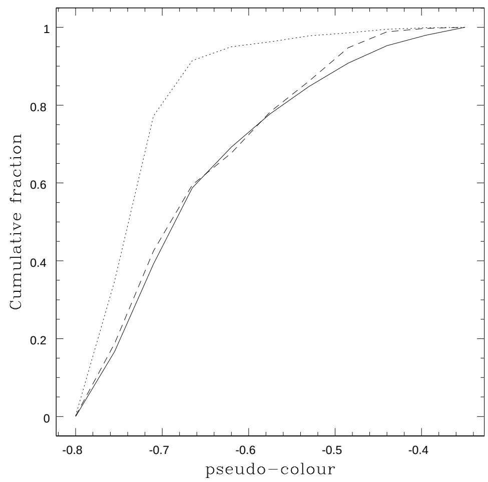

Figure 3. Observed cumulative distribution function with pseudo-colour in NGC 1818 (solid line; full stellar sample) compared with an artificial stellar population with zero binary fraction ($f_{\rm b}$, dotted line), and the best-fitting (r.m.s.) uniform mass-ratio distribution of $f_{\rm b} = 0.62 \pm 0.05$ (dashed line). See Hu et al. (2009) for more details.

of $f_{\rm b} = 0.62 \pm 0.05(1\sigma)$ (dashed line). Note that the fit is poor at larger pseudo-colours. This is always the case and is due to the presence of unresolved higher-order systems.

The combination of the results presented in this and the previous sections triggers a number of questions. Do high binary fractions affect mass segregation at early times or the relaxation of substructure? Do they leave observational signatures? NGC 1818 is several crossing times old, so that the binary population should have been modified by dynamical interactions. In particular, soft (i.e., wide) binaries are expected to have been destroyed by this age. Therefore, the high binary fraction found for F stars suggests that these binaries are relatively 'hard' and able to survive dynamical encounters.

5. Uncertainties abound

For any cluster, but particularly for the lower-mass end of the cluster mass function, it seems clear that the effect of binaries, mass segregation and the dynamical alteration of mass functions by two-body relaxation are important factors that cannot be ignored.

We recently explored the usefulness of the diagnostic age versus mass-to-light-ratio diagram in the context of YMCs and Galactic open clusters (e.g., Smith & Gallagher 2001; Mengel et al. 2002; McCrady et al. 2003, 2005; Larsen et al. 2004; Bastian et al. 2006; Goodwin & Bastian 2006; Moll et al. 2008; see de Grijs & Parmentier 2007 for a review). This diagram is often used in the field of extragalactic young to intermediate-age massive star clusters to constrain the shape of their stellar IMF, as well as their stability and the likelihood of their longevity. Based on high-resolution spectroscopy to obtain the objects' integrated velocity dispersions, σ, and on high-spatial-resolution imaging to obtain accurate projected half-light radii, $r_{\rm hl}$, most authors then apply Spitzer's (1987) equation,

$$M_{\rm dyn} = \eta \frac{r_{\rm hl}\sigma^2}{G}, \tag{5.1}$$

to obtain the dynamical cluster masses, $M_{\rm dyn}$ (G is the gravitational constant and $\eta \approx$

9.75 is a dimensionless parameter which is usually assumed to be constant; but see Fleck et al. 2006; Kouwenhoven & de Grijs 2008).

Despite a number of simplifying assumptions (see, e.g., de Grijs & Parmentier 2007 for a review; Moll et al. 2008), one can get at least an initial assessment as to whether a given cluster may be (i) significantly out of virial equilibrium, in particular 'super-virial', (ii) significantly over- or underabundant in low-mass stars, or (iii) populated by a significant fraction of binary and higher-order multiple systems. This has led to suggestions that, in the absence of significant external perturbations, young massive clusters (YMCs) located in the vicinity of the simple stellar population models and aged $\geqslant 10^8$ yr may survive for a Hubble time and eventually become old GC-like objects (e.g., Larsen et al. 2004; Bastian et al. 2006; de Grijs & Parmentier 2007).

Using the massive young Galactic cluster Westerlund 1 as a key example, we cautioned that stochasticity in the IMF introduces significant additional uncertainties (de Grijs et al. 2008). For Galactic open clusters, the effect of binaries within clusters may well account for most of the displacement of the observed cluster positions to below the model curves in de Grijs et al. (2008). Kouwenhoven & de Grijs (2008) pointed out that if the velocity dispersion of binary systems were similar to the velocity dispersion of the cluster as a whole, the *observationally measured* velocity dispersion would overestimate the mass of a cluster. Based on a comparison with Kouwenhoven & de Grijs (2008), in de Grijs et al. (2008) we concluded that the vast majority of our sample of open clusters are indeed expected to be binary dominated.

We also note that the cluster masses may well have been overestimated by factors of a few through the universal use of Eq. (5.1). In particular, for highly mass-segregated clusters containing significant binary fractions, a range of stellar IMF representations, and for combinations of characteristic relaxation timescales and cluster half-mass radii, the adoption of a single scaling factor $\eta \approx 9.75$ introduces systematic offsets. To correct for these, we would need to adopt smaller values of η (e.g., Fleck et al. 2006; Kouwenhoven & de Grijs 2008), and this would thus lead to dynamical mass overestimates if $\eta = 9.75$ were assumed.

We have now reached a stage in star cluster studies in which it is imperative to combine observational, theoretical and numerical modelling efforts to make the next major leap in our physical understanding. The level of detail required to make significant progress necessitates the combined forces of modellers in the fields of stellar population synthesis, N-body simulations and smooth-particle hydrodynamics, as well as observers with a good grasp of the intricacies of curent-generation data problems and reduction issues. It looks, therefore, that the conventional small research teams of the past may soon need to expand and become more inclusive to make significant and exciting headway.

Acknowledgements

I thank the Scientific Organising Committee of IAU Symposium 266 for their vote of support to deliver this review talk. I would also like to highlight that most of the results presented in this contribution are based on PhD thesis work by Richard Allison (University of Sheffield), Qiang Liu and Yi Hu (National Astronomical Observatories, Chinese Academy of Sciences). I acknowledge funding to attend this meeting from the Royal Society, the International Astronomical Union and the Learned Societies Fund of the University of Sheffield.

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